Final Report — Phase II

BLAST-ACTUATED CLOSURE VALVES FOR PERSONNEL-TYPE SHELTERS

By: R. KIANG

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D.C.

CONTRACT OCD-PS-64-201
WORK UNIT 1121C

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

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This report has been reviewed in the Office of Civil Defense and it has been determined that it does not provide an adequate technical base for determining the need for, and the selection of, blast closure devices for personnel shelters. The report is approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

BLAST-CLOSURE VALVES
By R. Kiang

Stanford Research Institute
February 1967
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DETACHABLE ABSTRACT

Three types of personnel-shelter blast-closure valves were tested. The measured closing times of the valves agreed in general with calculations made during Phase I of this project. The measured downstream bypassed pressures were about 15, 20, and 24 psig for incident shock pressures of 28, 31, and 40 psig, respectively, and were independent of the types of valves and their closing times. (Pressures within the shelter would be considerably less.) The results of the experiments suggest that a shock pressure of the order of a few milliseconds in duration would yield a comparable peak bypassed pressure immediately downstream of the valve whether the moving type closures studied were permitted to travel to the seat or were maintained in an open position (as a baffle) throughout the duration of the shock. An analysis was carried out capable of predicting the peak downstream leakage pressure.

ABSTRACT

Three types of personnel-shelter blast-closure valves were tested. The measured closing times of the valves agreed in general with calculations made during Phase I of this project. The measured downstream bypassed pressures were about 15, 20, and 24 psig for incident shock pressures of 28, 31, and 40 psig, respectively, and were independent of the types of valves and their closing times. (Pressures within the shelter would be considerably less.) The results of the experiments suggest that a shock pressure of the order of a few milliseconds in duration would yield a comparable peak bypassed pressure immediately downstream of the valve whether the moving type closures studied were permitted to travel to the seat or were maintained in an open position (as a baffle) throughout the duration of the shock. An analysis was carried out capable of predicting the peak downstream leakage pressure.

ACKNOWLEDGMENTS

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CONTENTS

ILLUSTRATIONS

TABLES

NOMENCLATURE

Term	Units	Definitions
A	in^2	Orifice opening area
A_1	in^2	Cross-sectional area of the shroud
a	in/sec	Speed of sound
C_D		Orifice coefficient
D	in	Diameter of valve plate
E	lb/in^2	Modulus of elasticity
g	in/sec^2	Gravitational constant
h	in	Thickness of valve plate
I	in^4	Moment of inertia of the valve plate
k	lb/in	Spring constant
L	in	Half-chord length of a Chevron-valve plate
m	$lb\text{-}sec^2/in$	Mass of the valve plate
P	lb/in^2	Pressure
P_o	lb	Blast force on the valve plate
R	$\frac{in\text{-}lb}{lb\text{-}^oR}$	Gas constant for air
T	^oR	Temperature
t_c	sec	Closing time
U	in/sec	Air particle velocity
W	$\frac{lb\text{-}sec}{in}$	Mass flow rate
w	lb/in	Load per unit length of the valve

NOMENCLATURE (Concluded)

Term	Units	Definitions
ρ	$\frac{lb\text{-}sec^2}{in^2}$	Mass per unit length of the valve plate
ρ_a	$\frac{lb\text{-}sec^2}{in^4}$	Density of air
δ	in	Distance between valve plate and valve seat
θ_{max}	rad	Maximum opening angle

I INTRODUCTION

A. Background

Blast shelters used to protect personnel from injury following a nuclear explosion must provide protection against thermal and nuclear radiation, blast-wave overpressure, ground shock, etc. This report on Work Unit 1121C, Phase II studies and experiments concerns itself with protection from overpressure.

Data from a number of physiological studies referenced on pages 75 to 79 of the Phase I Final Report[1]* dated August 1965, and in Tables F-I and F-II of the same report, appear to indicate that if an overpressure reaching a shelter ventilating port at 30 to 40 psig (incident) can be attenuated to a point where valve bypass into the shelter does not result in an interior overpressure exceeding 5 psig, the occupants will sustain little if any blast injury. The two tables are reproduced in Appendix B of this present report.

B. Objective

It has been the sole objective of studies and experiments in the present (second) phase, to check experimentally the theoretically calculated closing times of the candidate blast-actuated closure valves selected during Phase I of the task, reported in August 1965, as being most suitable for further investigation from the standpoint of reliability, simplicity, low-cost-construction, and low maintenance, etc.

Selection of candidate closures for test was made following studies of R Ravenko,[2] R. A. Breckenridge,[3] and R. S. Chapler.[4]

According to results of theoretical studies in Phase I, each of the four types would close in times of the order of a few milliseconds, which appeared adequate to limit the pressure rise in a 50-occupant

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* References are listed at the end of the report.

shelter (internal volume 5000 cubic feet) to below 5 psig, provided the valve closures were positively locked against rebound, and provided the initial, bypassed shock could be prevented from impinging directly upon shelter occupants or sensitive equipment located immediately downstream of the valve ports.

C. Scope of the Present Phase

The closing times for the four valves, obtained during Phase I, were all derived from theoretical calculations except in the case of the "Buships" valve reported by Chapler. This had been tested previously by USNCEL. It was therefore decided to carry out a limited number of significant experiments on models of the remaining three types during the present Phase II. It was intended first to compare the closing times of the experimental models with those calculated theoretically in Phase I.

While it was not practicable to generate, experimentally, shock-wave pulses comparable in duration to those produced by nuclear blast, it was necessary to generate pulses of a duration at least equal to or longer than the calculated closing times referred to above. It should be noted that one reason we are able to use a much shorter pressure pulse than that generated by a nuclear blast is that we are not measuring the rate and magnitude of overpressure buildup in a shelter volume during this Phase II.

Also to be measured in Phase II was the maximum bypassed shock-wave pressure immediately downstream* of the simulated valve openings, since sudden impingement by this bypassed pressure pulse upon fan filters, and ducts, etc. located in its immediate path could be destructive.

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* Downstream bypassed pressure for the purposes of this report are defined as "that pressure measured at no more than two feet downstream from the closure valve seat. It is not to be interpreted as the overall momentary overpressure in the general area of the shelter proper subsequent to closure of the valve. Pressure there would be considerably lower than in the immediate vicinity of the closure itself.

D. Test Equipment

The experimental valves were each to be mounted for testing on a common fixture mounted in turn at the upper end of a vertically disposed, explosively driven shock tube, used to generate the incident shock wave.

The "reflected pressure,"* the duration of the pressure pulse, and the closing times of the valves were to be measured, and the closing times compared with the theoretical closing times calculated in Phase I.

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* When an incident shock is impinging normal to a flat surface, the shock wave will be reflected and the pressure behind the reflected shock is generally more than twice the pressure behind the incident shock wave. This "reflected pressure" is the pressure load applied to any of the valve plates.

II PREPARATIONS FOR THE EXPERIMENT

A. Shock Tube

For reasons given below, it was decided to employ a locally available explosively driven shock tube to generate the shock pulses to be used for experimental simulation of the pressures that would be experienced by the ventilation openings of a domestic type personnel shelter located at a range of about 1 mile from ground zero of a 1-MT nuclear detonation. Calculations in Phase I of this project (Ref. 1) had indicated that cardidate closures selected for the present Phase II experiments should close in about 2 milliseconds after the onset of the advancing shock wave. It was essential therefore that certain basic requirements above others, be met:

(1) The explosively generated shock pulse must maintain its peak pressure for a time at least equal to and preferably greater than the calculated closing times referred to above in order that the measured closing times be meaningful, since the pressure rise to peak, accompanying shock arrival, can be considered almost as a step function on a millisecond time scale (see Ref. 1 for details).

(2) The shock tube had to be large enough in diameter to accommodate a valve model of convenient size. The SRI Poulter Laboratory has a 2-foot-diameter shock tube which can generate shock waves with peak pressures of from 20 to several thousand psig with pulse duration up to 2 milliseconds. This shock tube is explosively driven and vertically mounted in the ground with the open end (its test mounting face) near the ground level,[5] as shown in Fig. 1. For our tests, the driving section was to be the bottom half of the tube which would be loaded, prior to each shot, with the correct amount of primacord explosive. The hot gas resulting from detonation of the primacord would expand and drive a shock wave upward through the upper half--i.e., the driven section of the tube.

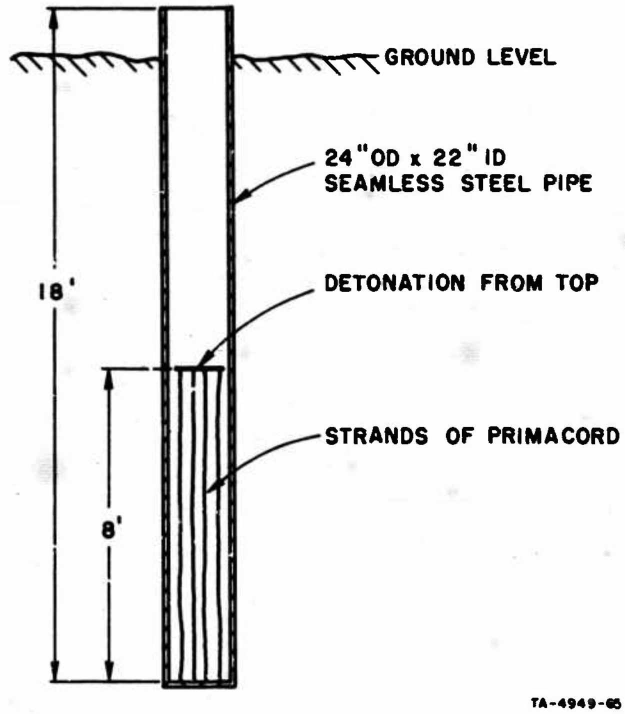

FIG. 1 THE SHOCK TUBE

B. Valve Models

The three types of blast-closure valve selected for testing in Phase II were (1) a Chevron valve, (2) a Flatplate valve, and (3) a Hinged flap or "swing" valve. Types 1 and 3 are illustrated and discussed in Ref. 3. The origin of the Type-2 concept is not known but it, like Types 1 and 3, is of familiar, simple, and potentially low-cost configuration and was considered therefore to be a suitable candidate. So far as is known, none of the three has been previously built and tested.

In order to accommodate to the 2-foot-diameter tube, the flat plate and the hinged flap or "swing" valves were fabricated to 1/2 scale: the full-size dimensions of the valves were determined by the ventilation requirements of the protected shelter.[1] A dimensional analysis was done in Phase I[1] to project the test results of the reduced-scale models to the full-size valves (see Sec. V). The model of the Chevron valve constituted an array of four full-size flaps representing a section of a

28-flap full size valve.[1] The "flaps" or "chevrons" for this valve are made of thin, curved spring steel (see Fig. 2), and flatten under blast pressure.

The detailed set-ups of these three types of valves are shown in Figs. 2, 3, and 4. The main fixture plate, which served as the support of the entire set-up, was made of steel armor-plate. All the remaining parts of the test fixture were made of mild steel. The dimensions shown in the figures were used in the theoretical calculations. The irrelevant dimensions are not shown, but the figures are drawn approximately to scale. The "relief" gap between the valve seat and the top of the shock tube was for controlled release of the explosive gas; it was maintained at the same spacing for the calibration shots and all testing shots.

The six numbers adjacent to black dots in the figures represent the locations of six gauges used in the test. The gauges were:

(1) Shock-arrival gauge
(2) Start gauge
(3) Stop gauge
(4) Kistler Model 601M quartz pressure transducer (Kistler gauge)
(5) LC-33 blast gauge[5] (blast gauge #608)
(6) LC-33 blast gauge (blast gauge #609).

A more detailed description of these gauges is given in Sec. II-C.

The thickness of the valve plate h is not specified in the figures since several different thicknesses were tested in order to see the response of different valve plates to the incident shock. These are specified for each shot, in Sec. III (Table II).

C. Instrumentation

The Kistler gauge and the blast gauge were both designed for pressure measurements. They are distinct in function in that the Kistler gauges were used to measure the reflected shock pressure, whereas the blast gauge, shaped in a pencil configuration with an aerodynamic forebody, could be used to measure the incident shock pressure (more

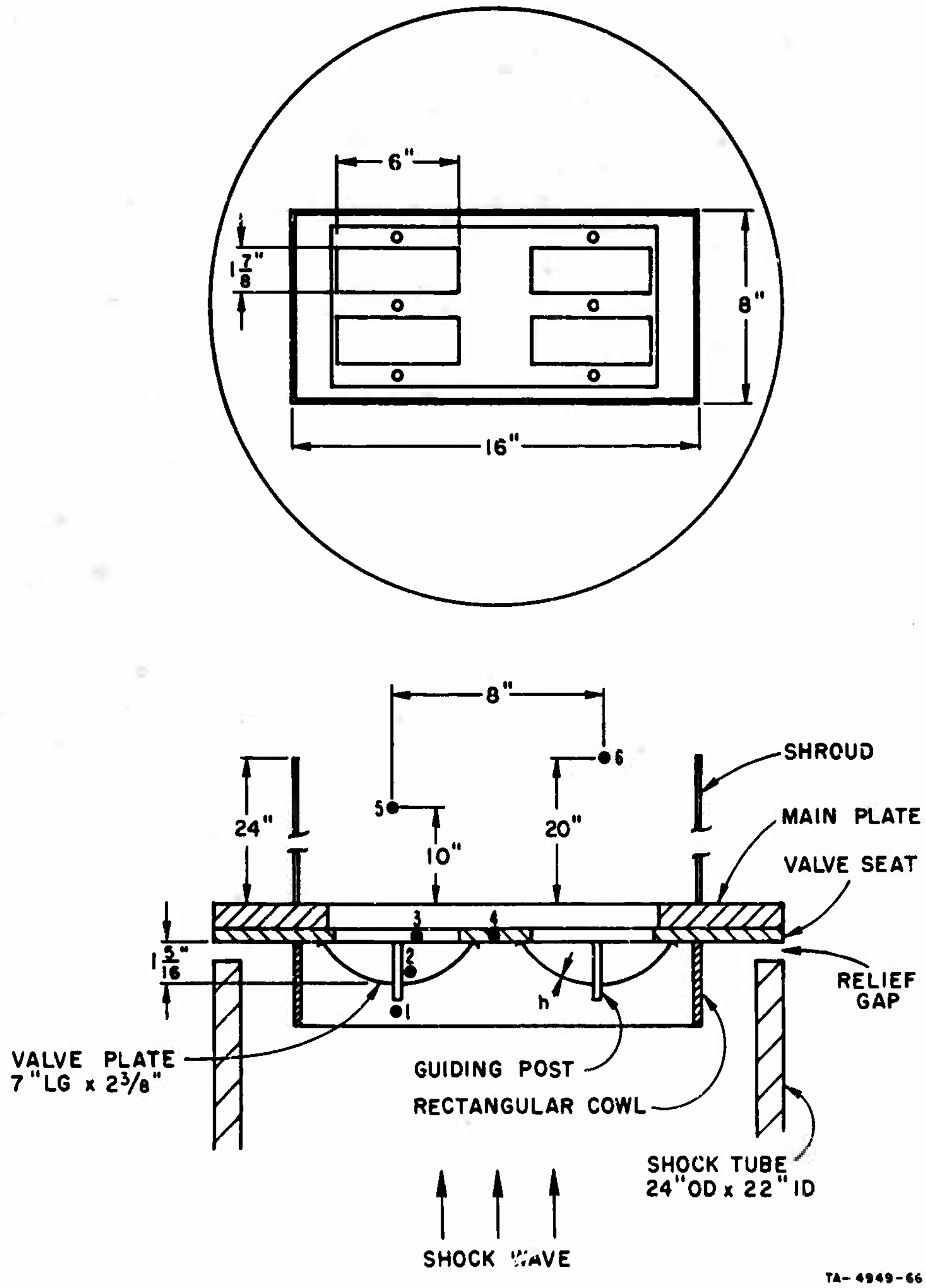

FIG. 2 CHEVRON-VALVE SET-UP

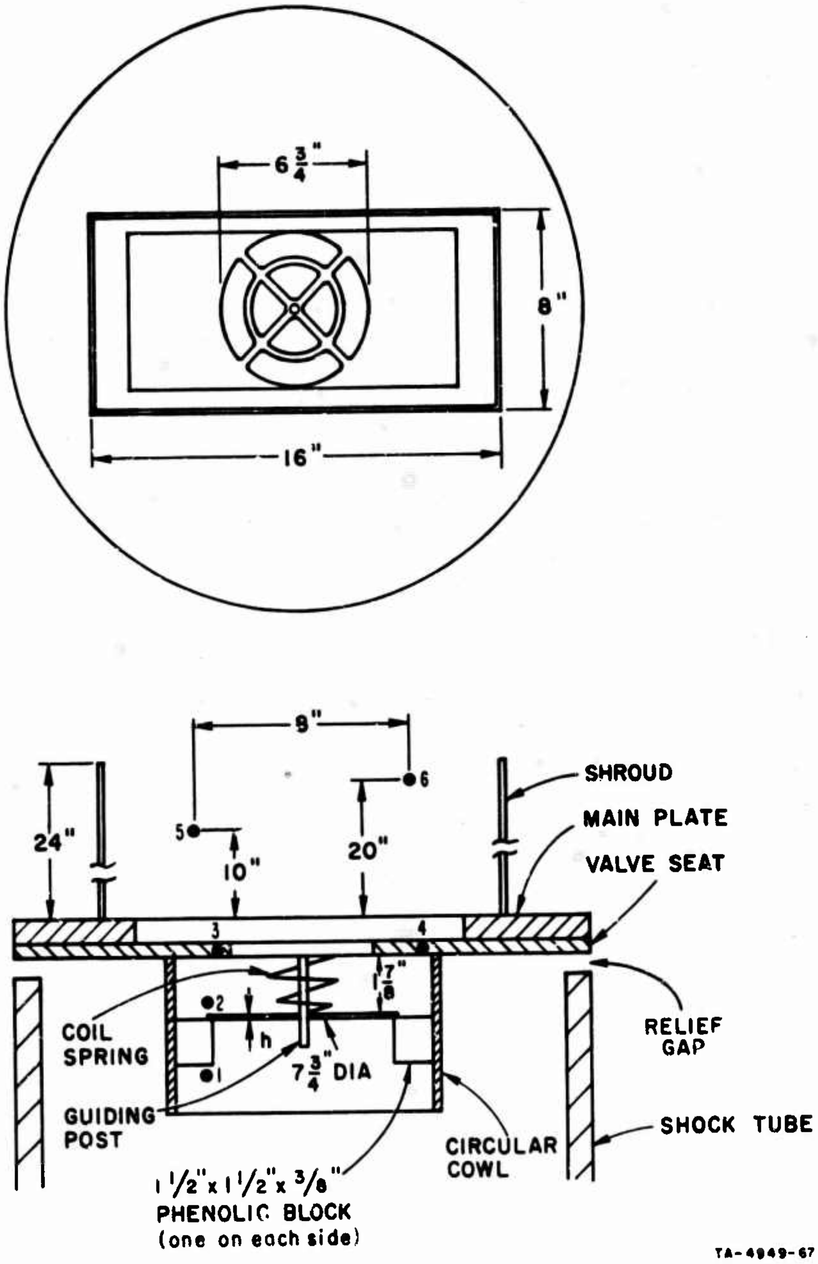

FIG. 3 FLAT-PLATE-VALVE SET-UP

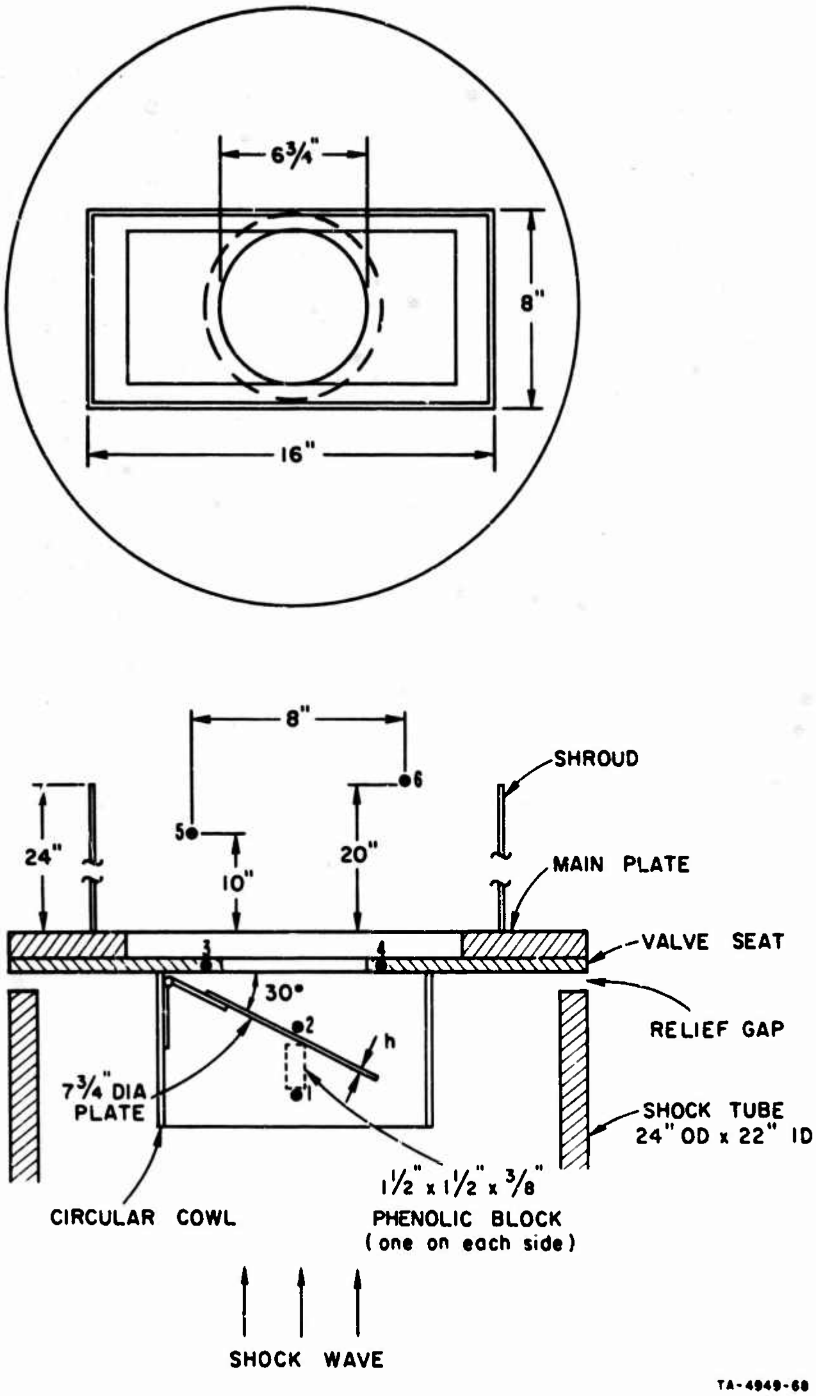

FIG. 4 SWING-VALVE SET-UP

specifically, the static pressure behind an incident shock wave). In the present test series these blast gauges were used to measure the downstream bypassed pressure.

The shock-arrival gauge (gauge 1 on Figs. 2, 3, and 4) was merely an open electrical circuit that was closed by the arriving shock wave. The closing "switch" in this case consisted of a small piece of copper foil and a metal pin sitting downstream from the foil (with reference to the direction of the advancing shock wave). The arrival of the shock wave simply drove the low-inertia foil into the pin, closing the circuit.

The start gauge (Gauge 2 on Figs. 2, 3, and 4) and the stop gauge (Gauge 3 on Figs. 2, 3, and 4) were identical and were designed to give an indication of the approximate time at which the valve plate started to move as well as the time it reached the valve seat. They were again initially open circuits. The open ends of each circuit were two parallel copper wires about 1/2 inch apart. The valve plate itself served as a bridge--i.e., the circuit was closed when the valve plate swept across the copper-wire ends. The stop gauge gave a very good indication of the time of closing; the start gauge, however, gave a somewhat delayed indication of commencement of the valve movement because it was necessary to mount the start gauge about 1/4-inch from the valve plate as shown in Figs. 2, 3, and 4. Nevertheless, the signals from both the shock-arrival gauge and the start gauge plus the calculable incident shock speed permitted a good estimate of the time when the valve plate actually started to move (see Fig. 6). However, there were a number of shots when either or both of these two gauges failed to register--because, for reasons unknown, the valve plate managed to close without contacting the two copper wires (see Table II, Col. 7).

Throughout the test series the electrical signals from all gauges were recorded on an Ampex FR100A recorder. During the initial calibration shots, oscilloscopes were also used to obtain pressure profiles.

III EXPERIMENTS

A. Calibration Shots

The purpose of the calibration shots was to find the relationship between the length of primacord used and the resulting reflected pressure that would represent the pressure loading on the valves. Because it was the reflected pressure rather than the incident pressure that was of interest, the eight calibration shots were carried out with the valves replaced by a 1/2-inch steel plate which sealed the openings on the valve seat (Figs. 2 and 3). Three Kistler gauges were installed in this cover plate to record the reflected pressure. Oscilloscopes were used to trace the reflected pressure profile (vs. time). A typical pressure profile is shown in Fig. 5. The top and the bottom traces are records from the same Kistler gauge, but have different time scales.

In our first experiments, the primacords were detonated from the bottom rather than from the top, as shown in Fig. 1, during Shot 1. The resulting pressure profile showed a rapid exponential decay immediately following the initial peak pressure. For reasons given in Sec. II-A, this was not at all desirable. Shot 2 was then tried with detonation from the top. The pressure profile thus obtained was highly successful. The peak pressure held almost constant for longer than one millisecond before decay started. For example, the pressure profile shown in Fig. 5 indicated a reflected pressure of about 160 psig and lasted for about 1.5 milliseconds. The remaining shots were all detonated from the top.

Table I summarizes the results of the calibration shots. Indicated reflected pressures and pressure pulse durations are average values of the three Kistler gauge recordings.

Table I

REFLECTED PRESSURES AND PULSE DURATIONS

	Strands of Primacord*	Reflected Pressure, P_3 (psig)	Pressure Pulse Duration (ms)
Chevron Valve Seat	4	95	1.6
(Rectangular Cowl)	5	110	1.5
	6	150	1.5
Flat-Plate Valve	4	90	2.0
Seat	5	115	1.9
(Circular Cowl)	6	135	1.7

* Primacord explosive used was 25 grains per foot. Each strand is 9 feet long.

B. Valve Testing

Following the eight calibration shots, 17 Tests (Nos. 9-25) were conducted with the cover-plate removed and replaced by actual valves. The test set-ups were as shown in Figs. 2, 3, 4, and 6.

During Shots 9 and 10 (see Table II) one Kistler gauge was still retained in the valve seat to measure the reflected pressure profile. The reflected-pressure profiles and pulse durations measured during these two shots were comparable to the equivalent calibration shots and suggested eliminating this gauge. An additional reason for eliminating this gauge is that the repeatability of results from a given charge of primacord appeared to be well established during previous tests in the series and that the reflected pressure and pulse duration could therefore now be predicted from the length and number of primacord strands loaded prior to a shot.

Shots 9 to 13 were tests without downstream shroud (see Fig. 2) and blast gauges (Fig. 6). Shots 14 and 15 were tests with shroud and with blast gauges #608 and #609 placed 10 inches from the main plate (Fig. 7). For other shots using blast gauges, #608 gauge was still placed 10 inches from the main plate but gauge #609 was placed 20 inches from the main plate as shown in Figs. 2 and 3.

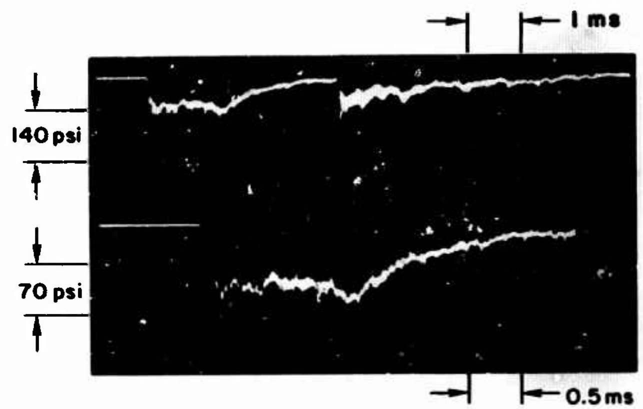

FIG. 5 TYPICAL REFLECTED-PRESSURE PROFILE

FIG. 6 TEST SET-UP WITHOUT SHROUD

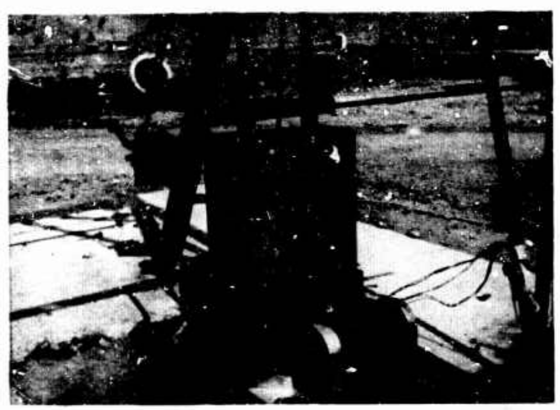

FIG. 7 TEST SET-UP WITH SHROUD

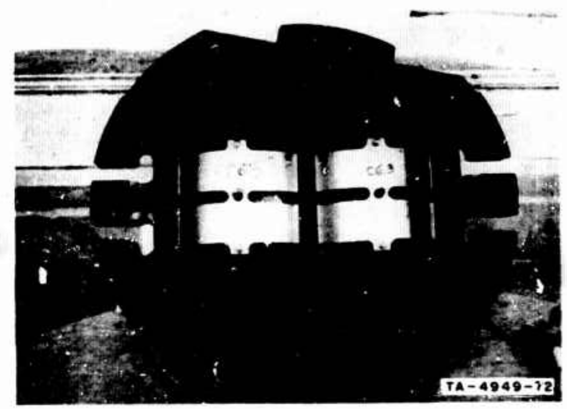

FIG. 8 CHEVRON-VALVE ARRANGEMENT

Table II

VALVE TEST RESULTS

SHOT NO.	STRANDS OF PRIMA-CORD	REFLECTED PRESSURE, P_3 (psig)	PULSE DURATION (ms)	TYPE OF VALVE	VALVE PLATE THICKNESS, h (mils)	CLOSING TIME, t_c (ms)	PREDICTED CLOSING TIME, t_c (ms)	MAXIMUM DOWNSTREAM LEAKAGE PRESSURE, P_2 #608 (psig)	#609* (psig)	TIME BETWEEN ESTIMATED START & BLAST GAUGES REGISTER #608 (ms)	#609 (ms)	REMARKS
9	6	150	1.5	Chevron	20.50	-,-	0.5, 0.8					20-mil valve plate failed
10	6	135	1.7	Swing	58	2.0	1.4					
11	6	135	1.7	Flat-Plate	58	1.3	1.1					No Kistler gauge from here on
12	6	150	1.5	Chevron	58, 77	1.3, --	0.8, 0.9					
13	4	90	2.0	Flat-Plate	79	1.9	1.6					
14	5	115	1.9	Flat-Plate	79	1.5	1.4	20	20	0.8	0.8	Both blast gauges 10 inches from main plate
15	4	90	2.0	Flat-Plate	63	(6.2)	1.4	15	13	0.9	0.9	
16	5	115	1.9	Flat-Plate	63	1.4	1.3	18	23	0.8	1.3	#608 10 inches, #609 20 inches from main plate from here on
17	6	135	1.7	Flat-Plate	63	(3.8)	1.2	23	28	0.8	1.4	
18	4	90	2.0	Flat-Plate	63	1.7	1.4	13	15	0.9	1.5	
19	4	90	2.0	Flat-Plate	63	--	1.4					No blast gauge used
20	4	90	2.0	Flat-Plate	63	(5.2)	1.4					
21	6	135	1.7	Swing	63	(3.8)	1.4	26	21	0.8	1.3	#608 10 inches, #609 20 inches from main plate
22	6	150	1.5	Chevron	63	1.8, 1.3	0.7, 0.7	26	23	0.8	1.3	
23	6	150	1.5	Chevron	63	(3.7), 1.2	0.7, 0.7	26	22	0.7	1.2	
24	5	110	1.5	Chevron	63	1.4, 1.4	1.0, 1.0	20	17	0.8	1.3	
25	4	95	1.6	Chevron	63	1.5, (2.3)	1.1, 1.1	16	14	0.7	1.3	
26	4	95	1.6	None				30	23			Chevron valve seat
27	4	95	1.6	None				15	8			Chevron valve seat. Shroud removed
28	4	95	1.6	None				8	8			Flat-plate valve seat. Shroud removed

* #608 and #609 are two identical blast gauges placed at two different positions downstream of the valve.

Because there were two pairs of valve plates in our Chevron valve model (Fig. 8), it was possible to use valve plates of two different thicknesses in one shot. This was done in Shots 9 and 12.

The Swing valve was tested only twice throughout the entire test program. The reason for this was twofold. First, the performance of the Swing valve was comparable with but definitely not superior to the Flat-Plate valve. Hence there was no reason to carry through with all the tests for both of them. Second, the Swing-valve plate and the hinge connecting it to its seat turned out to be more expensive in construction than the Flat-plate valve, which needed no supports other than a simple central guiding post.

The valve plates of all valves were deformed after the first shot. However, they were still as responsive when subjected to a second or a third shock wave. Shots 18, 19, and 20 (Table II) were made using the same valve plate.

A typical tape-recorder record of a shot is shown in Fig. 9. Note that the estimated starting motion of the valve preceded the registering signal of the start gauge. This estimation was based on the signals from the shock-arrival gauge and the start gauge, and on the incident shock speed, as was mentioned in Sec. II-C.

The results of all valve tests summarized in Table II permit a number of observations and remarks:

(1) In Column 7 of Table II it can be seen that the closing times in parentheses were inordinately long compared to the remainder. It is conjectured that during these shots an extraordinary amount of friction was developed between the hole in the valve plate and the surface of the guide post (Figs. 2 and 3) probably due to lateral "float" of the plate. Heavy longitudinal scoring on the guidepost and tearing around the guide hole support this supposition.

(2) The rest of the closing times were all close to the theoretically predicted closing times given in Column 8 (equations for calculating the predicted closing time are given in Appendix A). The fact that all measured closing times were longer than the predicted times suggests that either the aforementioned friction was

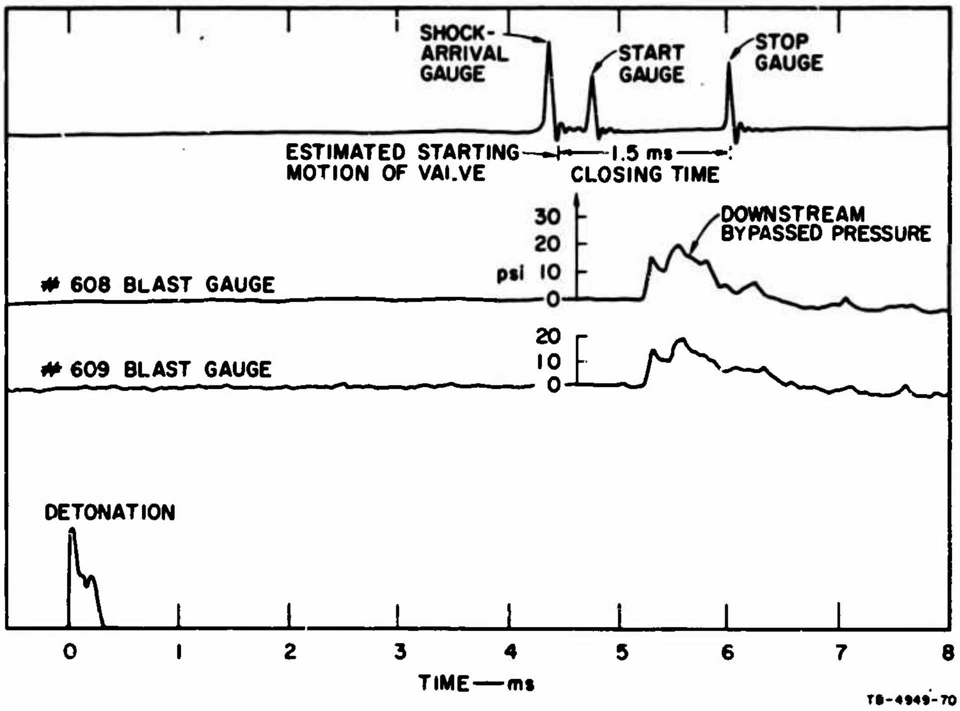

FIG. 9 TYPICAL SHOT RECORD

never completely absent or the closing-time equations are not entirely realistic. However, the fact that some of the minimum closing times are almost identical to the calculated ones seems to validate the equations. Furthermore, the larger differences between the measured and the calculated closing times in the case of Chevron-valve tests are consistent with the excessive rim tearing of the valveplate guide hole observed in the tested Chevron valve plates.

(3) In Column 9 it can be seen that the measured downstream bypassed pressures were about 15, 20, and 24 psig for 90, 115, and 140 psig of reflected pressures, respectively. Furthermore, the maximum bypassed pressures were independent of the closing times and were increasing almost linearly with the reflected pressure for each type of valve. This was not expected prior to the experiments, but an explanation was provided by a close examination of the test record. It can be seen in Fig. 9 that the sudden jump of the downstream leakage pressure appeared midway in the closing-time interval. This would seem to indicate that the bypassed pressure pulse had traveled about 10 inches downstream before the valve was even closed. Therefore the performance of the valve had no effect on the maximum bypassed pressure. The analysis in Sec. IV is essentially based on this observation.

(4) Column 10 indicates that the times for the bypassed pressures to reach the blast gauges were also independent of the type of valve. In addition, they appeared to be independent of the reflected pressures. This is probably because the pressure range covered in these tests was very limited.

C. Open-Port Shots

The last three shots (Nos. 26-28) in Table II were performed with the valve plate omitted for comparison with results from shots with the valve plates in place. In all other respects conditions were the same. The Chevron valve (Fig. 8) with the four rectangular ports open (i.e. valve plates removed) was used for Shots 26 and 27; the downstream shroud was removed for No. 27. For Shot 28 a circular ported valve (Fig. 3) was used with the valve plate and downstream shroud removed.

Removal of the shroud for Shots 27 and 28 significantly reduced the bypassed pressures. However, in the case of a real shelter, there would undoubtedly be ducting immediately downstream of the ventilating port, accommodating a fan and filter. This ducting would have much the same effect as the experimental shroud in confining and channeling the bypassed blast pressure, which could damage or destroy both fan and filter.

The results of Shots 27 and 28, however, were quite close to those obtained by U.S. Naval Civil Engineering Laboratory during their tests of the Buships type of valve* (without a shroud), where the bypassed pressure measured was about 10 psig from an incident pressure of about 50 psig.

* See Ref. 1 and the references cited therein.

IV DOWNSTREAM BYPASSED PRESSURE

A. Theory

The downstream-bypass-pressure profiles, a typical one of which is presented in Fig. 9, all showed a stepwise jump at the beginning. This sudden jump indicated that the downstream bypassed pressure was actually a shock wave propagating down the shroud. In the case of a real shelter's closure valve, the shroud could be formed by the wall thickness of the shelter boundary plus downstream ductings. The maximum bypassed pressures were observed to be independent of the type of valve tested and its closing time. This, plus the additional fact that a sudden rise of the downstream bypassed pressure was recorded when the valve plate was only partially closed, indicated that the incident shock wave was partially transmitted downstream due mainly, it is believed, to the sudden mass flow across the valve when the upstream pressure was raised instantaneously by the reflected shock. The following theoretical model was developed to enable a study to be made of the downstream bypassed pressure (Fig. 10).

In Fig. 10, the large section on the left represented roughly the 2-foot-diameter shock tube, and the small section on the right represented the shroud which had a cross-sectional area of A_1. The moving valve plate was replaced by a stationary baffle simulating a partially closed valve. Regions 1, 2, 3, and 4 have different pressures, densities, and temperatures. Region 1 represents ambient atmospheric condition. The high-pressure region 3 is separated from the low-pressure region 2 by the orifice-type opening of Area A. Two assumptions are made in the following analysis: (1) That the steady-state orifice flow equation could be used in this transient situation; and (2) that the transmitted shock wave has formed at least a clearly defined shock front at a distance 10 inches downstream of the valve seat opening where the blast gauge is placed. The first assumption has no further justification beyond the fact that the results of the analysis come very close to

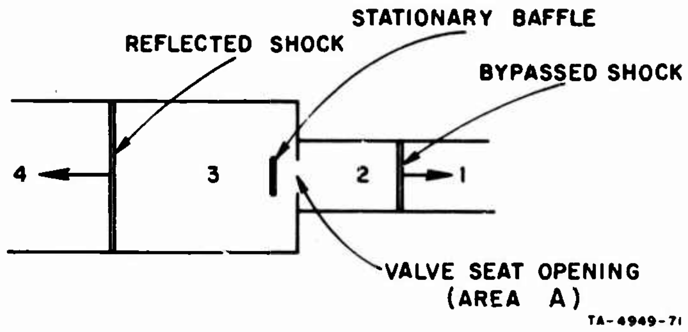

FIG. 10 MODEL FOR THE STUDY OF DOWNSTREAM BYPASSED PRESSURE

the experimental results (Sec. IV-B). The second assumption is justified by the stepwise jump of the experimentally measured downstream bypassed pressure profile.

The orifice flow equation is a semi-empirical formula that gives the approximate mass flow rate W up to and beyond the choking condition:[6]

$$W = C_D A \left(\frac{P_3^2 - P_2^2}{gRT_3} \right)^{1/2} \tag{1}$$

where C_D is the orifice coefficient. Other quantities are defined in the List of Symbols at the front of the report; subscripts correspond to the regions in Fig. 10.

By continuity, the mass influx from the orifice must be equal to the mass of air "engulfed" by the secondary shock per unit time:

$$W = \rho_2 U_2 A_1 \quad . \tag{2}$$

Combining Eqs. (1) and (2) gives

$$\rho_2 U_2 A_1 = C_D A \left(\frac{P_3^2 - P_2^2}{gRT_3} \right)^{1/2} \quad . \tag{3}$$

The density ρ_2 and particle velocity U_2 are given by the Rankine-Hugoniot relations:[7]

$$U_2 = \frac{a_1}{\gamma_1}\left(\frac{P_2}{P_1} - 1\right)\left(\frac{\dfrac{2\gamma_1}{\gamma_1 + 1}}{\dfrac{P_2}{P_1} + \dfrac{\gamma_1 - 1}{\gamma_1 + 1}}\right)^{1/2} \tag{4}$$

$$\frac{\rho_2}{\rho_1} = \frac{1 + \dfrac{\gamma_1 + 1}{\gamma_1 - 1}\dfrac{P_2}{P_1}}{\dfrac{\gamma_1 + 1}{\gamma_1 - 1} + \dfrac{P_2}{P_1}} \quad . \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3) gives a single equation for P_2, the downstream bypassed pressure:

$$\frac{\rho_1 a_1 A_1}{\gamma_1} \cdot \frac{P_{21} - 1}{1 + \mu_1 P_{21}}\left[\frac{2\gamma_1}{\gamma_1 + 1}\left(P_{21} + \mu_1\right)\right]^{1/2} = C_D A\left(\frac{P_3^2 - P_2^2}{gRT_3}\right)^{1/2} \tag{6}$$

where

$$P_{21} \equiv \frac{P_2}{P_1} \text{ and } \mu_1 \equiv \frac{\gamma_1 - 1}{\gamma_1 + 1} \quad .$$

B. Approximations and Simplifications

Because the pressure ranges we were interested in were quite limited, certain approximations could be made in Eq. (6), as follows:

(1) P_{21} was of order 2, $\mu_1 = 0.167$ for $\gamma_1 = 1.4$, so

$$P_{21} + \mu_1 \approx P_{21} \quad .$$

(2) $\mu_1 P_{21} \approx 0.33$, which was less than unity, so a binomial expression could be used:

$$\frac{1}{1 + \mu_1 P_{21}} \approx 1 - \mu_1 P_{21} \quad .$$

(3) P_3^2 was about 10 times larger than P_2^2, so

$$(P_3^2 - P_2^2)^{1/2} \approx P_3 \quad .$$

With these approximations made, Eq. (6) was simplified to

$$(1 - \mu_1 P_{21})(P_{21} - 1)\left(\frac{2\gamma_1}{\gamma_1 + 1} P_{21}\right)^{1/2} = \frac{\gamma_1}{\rho_1 a_1} \cdot \frac{A}{A_1} \cdot \frac{C_D P_3}{(gRT_3)^{1/2}} \quad . \tag{7}$$

C. Numerical Results

Applying Eq. (7) to the valve configurations we have tested gives the following numerical results:

$$\frac{A}{A_1} = 0.156 \qquad \text{Flat-Plate valve seat}$$

$$\frac{A}{A_1} = 0.195 \qquad \text{Chevron valve seat.}$$

C_D is less than, but close to unity. The actual value of C_D used was determined by setting P_{21} in Eq. (7) equal to the measured value of P_{21} of Shot 14. It turned out that $C_D = 0.975$, and this value of C_D was then used for the rest of the shots.

The numerical results of the calculated bypassed pressures are given in the third-to-last column of Table III. Measured bypassed pressures are listed in the second-to-last column for comparison. The last column, which is calculated from the reflected pressures listed under the second column, is for the purpose of immediate comparison with the bypassed pressures.

Table III

CALCULATED BYPASSED PRESSURES

Shot No.	Reflected Pressure, P_3 (psia)	Reflected Shock Temp, T_3* (°R)	Pressure Ratio, P_{21} [Solution of Eq. (7)]	Calculated Bypassed Pressure, P_{2g} (psig)	Measured Bypassed Pressure, P_{2g} (psig) #608, #609	Incident Shock Pressure (psig)
14	129.7	1100	2.36	20	20, 20	32
15	104.7	1000	2.13	16.6	15, 13	28
16	129.7	1100	2.36	20	18, 23	32
17	149.7	1200	2.52	22.3	23, 28	40
18	104.7	1000	2.13	16.6	13, 15	28
21	149.7	1200	2.52	22.3	26, 21	40
22	164.7	1200	2.32	19.4	26, 23	42
23	164.7	1200	2.32	19.4	26, 22	42
24	124.7	1100	2.04	15.3	20, 17	32
25	109.7	1000	1.96	14.1	16, 14	28

* T_3 obtained from Ref. 8.

V PROJECTED PERFORMANCE OF FULL-SCALE VALVES

All three types of valves were originally designed to supply sufficient ventilating air for a 50-person shelter during the normal ventilation operation.[1] As mentioned in Sec. II-B, the experimental Flat-Plate-valve and Swing-valve models tested were made 1/2-scale in order to fit the 2-foot-diameter shock tube. Therefore, comparison of the performances of these three types of valves should be made only if all are of the same size.

In anticipation of the reduced-scale-model test, a dimensional analysis was carried out in Phase I (Sec. IV of Ref. 1), so as to project the results of a reduced-scale model to a full-size one. The result of the dimensional analysis can be stated as follows:

> If the model and the prototype are geometrically similar and made of the same material, then all pressures, including the downstream bypassed pressure, measured on the reduced-scale experimental model test should remain the same for the full-sized prototype, and the closing time of the prototype should be calculated by multiplying the closing time measured on the reduced-scale model by the reciprocal of the reducing factor.

Therefore, the results in Table II remain unaltered except that the closing times of the experimental Flat-Plate and Swing valves should be multiplied by 2 to obtain the closing times of the full-size valves. It may be recalled from page 4 that each individual flap of the Chevron valve is full-sized; therefore no modification is needed for the Chevron-valve test data.

VI DISCUSSIONS AND CONCLUSIONS

(1) The calculated valve closing times came generally quite close to the experimental closing times (Table II), which indicated that the equations for closing times (see Appendix A) derived in Ref. 1 were a fair mathematical representation. A few of the exceptionally long closing times measured were caused by excessive friction induced between the valve plates and their guiding posts.

(2) Maximum downstream bypassed pressures proved to be independent of the closing times and were also independent of the type of valve (Sec. III-B and Table II).

(3) Downstream bypassed pressure, due mainly to the sudden mass flow across the valve, was in the form of a transmitted shock propagating down the shroud (Secs. III-B and IV-A).

(4) Maximum downstream bypassed pressures of the closing-type valves tested can be adequately predicted with the theory given in Sec. IV (see particularly Sec. IV-C).

(5) The results of the experiments suggest that a shock pressure of the order of a few milliseconds in duration would yield a comparable peak bypassed pressure immediately downstream of the valve whether the moving-type closures studied were permitted to travel to the seat or were maintained in an open position (as a baffle) throughout the duration of the shock. However, faster-closing devices might yield further attenuation.

(6) Due to the short pulse duration of the incident shock, in contrast to the much longer pulse duration of a nuclear blast wave, only the measured closing times and the maximum downstream bypassed pressures are meaningful. The profile of the downstream bypassed pressures as shown in Fig. 9 should not be taken as the actual profile that would occur if an entire valve system is subjected to a nuclear blast wave.

(7) The maximum measured downstream, bypassed pressures listed in Table III are seen to be over one-half of the incident pressures. That is, these three simple valves reduce the bypassing pressures to about 1/2 of the incident pressures. Breckenridge[9] achieved a 1/4 reduction from an incident pressure of about 30 psig during the test of his own design of blast-closure valve. It is speculated that further reduction of the bypassing pressure may still be possible through a change of design. A preliminary proposal for achieving this is given in Sec. VII.

VII TECHNICAL RECOMMENDATIONS

The valve-closing-time experiments performed in the present phase suggest that blast-actuated moving closures with closing times of the order of one millisecond would reduce an entering overpressure of 40 psig to only about half that value in the immediate area of the downstream exit of the closure. Breckenridge (Ref. 9, page 23, Fig. 16) introduced a delay passage about 22 feet long, upstream of a moving closure, which in turn was succeeded by a plenum chamber. From Fig. 16 of Ref. 9 it appears feasible to reduce a 40-psi entering-blast-wave overpressure by about 75% as measured at a point 2 feet 10 inches downstream of the closure and by a total of about 96% as measured at a point within a 32-foot^3 plenum chamber located farther downstream of the closure. It is borne in mind that in most experiments in the series, the plenum represented a dead-end expansion chamber and that therefore the pressure measurements did not represent values that would have been obtained had the plenum opened into a shelter proper.

It may be impracticable in many instances to provide for an upstream delay passage in the form discussed, yet since the bypassed pressures listed in Table II of this report are very likely to be destructive to most commercially available ducts, filter, fans, etc. and also injurious to personnel in the immediate path of such bypassed shock-wave pressures, auxiliary means for further reduction of these bypassed pressures must be sought. From the above it seems clear that a plenum (or expansion) chamber, connected to the downstream outlet of an open ventilation port to receive blast overpressure directly, and equipped with a restrictive exit port in its remote boundary, will indeed serve to substantially reduce the rate of pressure rise in the shelter proper.

However, such a system is incapable of limiting pressure build-up in the shelter in the event that the shock wave is of long duration (order of 1 sec).

It would appear according to Ref. 9 that interposition of a plenum or expansion chamber in a ducting system exposed to the entry of a shock wave results in substantial reduction in the rate of pressure rise seen at a restricted exit port in the remote boundary of the plenum. Although a slower rate of pressure rise is known to be helpful from a physiological point of view as indicated by the tests on smaller (than human beings) animals,[10] equivalent data applicable to human beings are all extrapolations rather than results of actual live testings; therefore, there is no decisive number available as to what rate of pressure rise is considered safe for human beings. For this reason, as a safe working value (and until more definite data are available), we have chosen to limit the maximum permissible pressure buildup in the shelter to 5 psig.

However if both entry to and exit from the chamber are left open, a long-duration shock wave such as one generated by a nuclear blast, will eventually permit the overpressure at the exit--and eventually in a shelter beyond--to rise to what could be an intolerable level.

It is conceivable that a "muffler" type of flow-restricter could also have some capability for prolonging the rise time. It nevertheless has drawbacks similar to those of the plenum above, in that it is incapable of limiting pressure buildup in a shelter or other closed space beyond it, when subjected to a long-duration shock wave. It seems, then, that a promising approach toward limiting pressure buildup in a shelter and simultaneously to control pressure-rise to an extent that damage to ventilating equipment and occupants is prevented or minimized, would be to employ a blast-attenuating system combining a moving closure preceded by an upstream delay-passage and followed by a downstream plenum chamber interposed between the closure and the shelter space beyond.

The only experimental effort known to the author that utilized an upstream delay passage, a moving closure, and finally a plenum chamber, was Breckenridge.[9] However in most of the test series discussed the plenum had no exit and acted as a closed expansion chamber.

A preliminary review of available information indicates that a further useful attenuation of bypassed blast pressure downstream of a closure, and prior to its entry into the shelter proper, might be achieved through one of the following approaches, alone or in combination:

(1) A baffle mounted exterior to the ventilating inlet

(2) A primary moving-closure

(3) A plenum chamber into which the initially bypassed overpressure would be directed and then, after traversing the plenum, go through a secondary closure in the chamber wall most remote from the primary closure (Fig. 12).

(4) A plenum chamber similar to (3) but with no secondary moving closure, and having several progressively more restrictive flow paths traversing partitions disposed between the primary closure and the final exit into shelter ambient (Fig. 11).

(5) An upstream delay passage of concentric-ring configuration with ports so disposed as to direct the entering blast wind in a circumferential and abruptly reversing path toward and into a central duct that connects directly with a moving closure. The bypassed blast from this closure could in turn be directed for further attenuation, into and through plenum-chamber systems under Item 1, above (see Fig. 13).

In view of the foregoing it is recommended that further work be done along the following lines:

(1) A further search be made of available literature on blast-actuated closure valves for personnel shelters, particularly at B.R.L.*

(2) Approaches other than the ones already considered be sought and investigated.

(3) A preliminary theoretical investigation be conducted to determine what combination of approaches might result in the lowest rate of pressure rise and level of buildup in a shelter.

(4) Experiments be performed to verify theoretical conclusions.

(Note: Since an ability to generate a shock wave of long duration is essential in testing the pressure response of a simulated personnel shelter, careful selection of shock-tube facilities would be of prime importance and would involve very close coordination with the custodian of such a facility in scheduling the experimental work.)

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* Ballistic Research Laboratories.

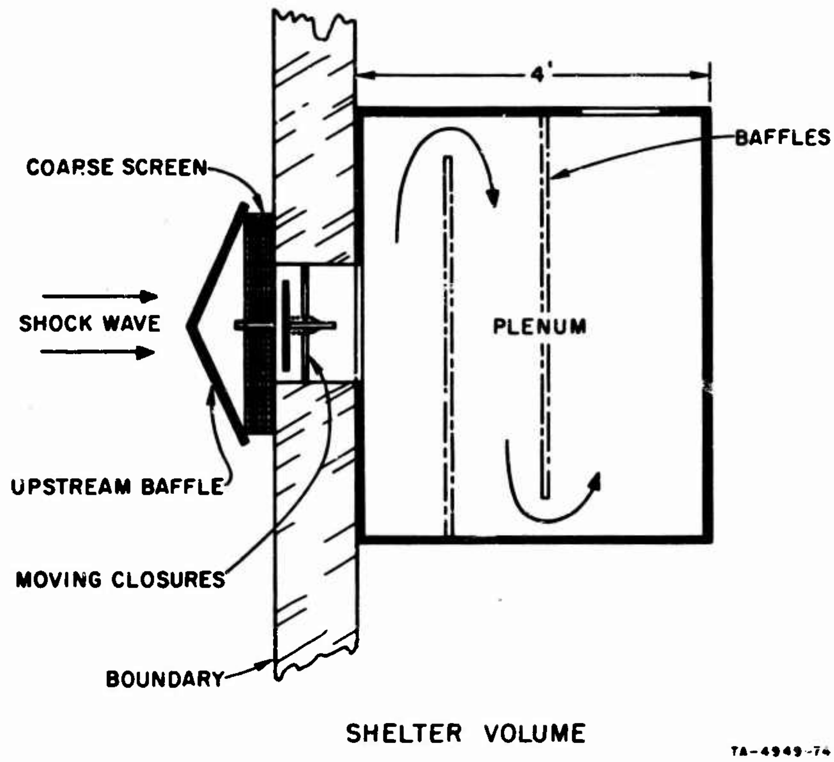

FIG. 11 CANDIDATE BLAST-ACTUATED CLOSURE VALVE WITHOUT SECONDARY CLOSURE BUT HAVING RESTRICTIVE BAFFLES DISPOSED WITHIN THE PLENUM

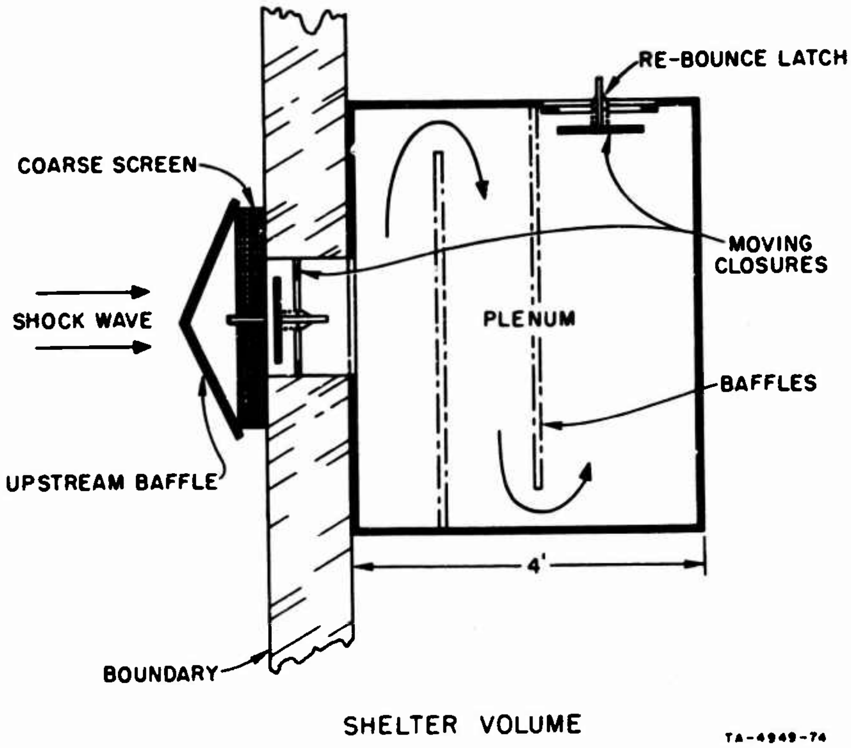

FIG. 12 CANDIDATE BLAST-ACTUATED CLOSURE VALVE WITH SECONDARY CLOSURE

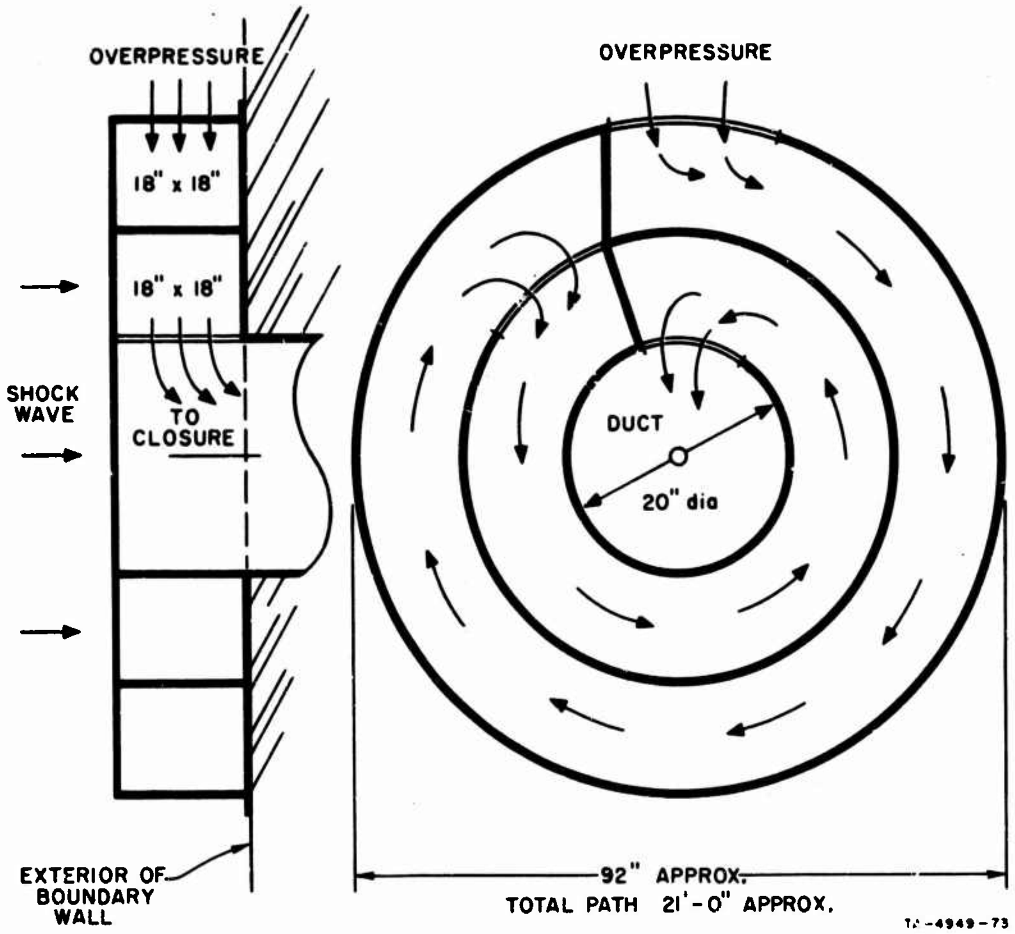

FIG. 13 CIRCULAR DELAY PATH TO BE USED WITH CANDIDATE BLAST-ACTUATED CLOSURE VALVE

Appendix A

CLOSING-TIME EQUATIONS

Appendix A

CLOSING-TIME EQUATIONS

The following equations for calculating the closing times of various types of valves were derived in Ref. 1:

Flat-Plate Valve

$$t_c = \sqrt{\frac{m}{k}} \cos^{-1}\left(1 - \frac{k\delta}{P_o}\right) \tag{A-1}$$

Swing Valve

$$t_c = \sqrt{\frac{5}{\pi} \frac{m\theta max}{PD}} \tag{A-2}$$

Chevron Valve

$$t_c = \left(\frac{2L}{\pi}\right)^2 \sqrt{\frac{\rho}{EI}} \cos^{-1}\left(1 - \frac{\delta EI}{\frac{4w}{\pi}\left(\frac{2L}{\pi}\right)^4}\right) . \tag{A-3}$$

Since $\cos^{-1}(1 - \varepsilon) \approx (2\varepsilon)^{1/2}$ for any $\varepsilon \ll 1$, Eqs. (A-1) and (A-3) can be simplified as follows:

Flat-Plate Valve

$$t_c = \left(\frac{2m\delta}{P_o}\right)^{1/2} . \tag{A-4}$$

Chevron Valve

$$t_c = \left(\frac{\pi\rho\delta}{2w}\right)^{1/2} . \tag{A-5}$$

Equations (A-2), (A-4), and (A-5) were used to calculate the closing times of Column 8 of Table II.

Appendix B

PHYSIOLOGICAL DATA

Table B-1

SHOCK-TUBE MORTALITY DATA FOR FAST-RISING, LONG-DURATION OVERPRESSURES WHEN INCIDENT AND REFLECTED PRESSURES ARE APPLIED ALMOST SIMULTANEOUSLY*

Animal Species	Overpressure for Indicated Mortality, psi						Threshold Pressure for Lung Injury, psi	
	1 Percent		50 Percent		99 Percent			
	Incident	Reflected	Incident	Reflected	Incident	Reflected	Incident	Reflected
Mouse†	7	20	11	30	15	44	4	10
Rabbit†	9	25	12	33	15	44	6	15
Guinea pig†	10	28	13	37	16	48	6	15
Rat†	10	28	14	39	18	53	8	19
Dog§	15	40	17	48	20	56	7	20
Man$^{\Delta}$		35-45		45-55		55-65		15-25

NOTE: All incident and reflected overpressures were empirically determined. Because of geometric factors there necessarily was not the same relation between incident and reflected overpressures for experiments with the smaller and the larger animals--e.g., the reflection of a given incident pressure is less in the presence of a larger animal than it is for the smaller animal.

* Reports WT-1467, TID-6056, TID-5564, and unpublished data from an AEC project being conducted at Lovelace Foundation, Albuquerque, New Mexico.

† Durations of overpressure were 6-8 sec.

§ Durations of overpressure were 400 ms.

Δ Tentative estimate for overpressure durations greater than 500 ms.

Source: Ref. 11, p. 36.

Table B-2

PRESSURE TOLERANCE OF THE EARDRUMS OF DOG AND MAN

Species	Maximum Pressures for the Noted Conditions		
	Minimal, psi	Average, psi	Maximal, psi
Dog*	5	31	90
Man†	5	20-33	43

* Data from 1953, 1955, and 1957 Nevada Field Tests; see WT-1467.

† Data from Zalewski. Human eardrum tolerance varies with age, hence the variation from 33 psi (for ages 1 to 10 years) to 20 psi (for ages above 20 years). See also Report TID-5564.

Source: Ref. 11, p. 39.

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13. ABSTRACT

Three types of personnel-shelter blast-closure valves were tested. The measured closing times of the valves agreed in general with calculations made during Phase I of this project. The measured downstream bypassed pressures were about 15, 20, and 24 psig for incident shock pressures of 28, 31, and 40 psig, respectively, and were independent of the types of valves and their closing times. (Pressures within the shelter would be considerably less.) The results of the experiments suggest that a shock pressure of the order of a few milliseconds in duration would yield a comparable net bypassed pressure immediately downstream of the valve whether the moving type closures studied were permitted to travel to the seat or were maintained in an open position (as a baffle) throughout the duration of the shock. An analysis was carried out capable of predicting the peak downstream leakage pressure.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Blast-closure valves						
Closing times						
Downstream leakage pressures						